Composite Overwrapped Pressure Vessels (COPV)

Part 1 - COPV Overview and Recent Liner Buckling Anomalies

Part 2 - Mars Environmental Rover Ultralight Propellant Tank Status

August 30, 2002

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Briefing Objectives

- Provide background on 'generic' COPV liner buckling and need for NASA action
- Provide background on the MER Ultralight Tank situation and how close we are to flight qualification
- Solicit support of the In-Space Propulsion Program

Benefits of COPV Technology

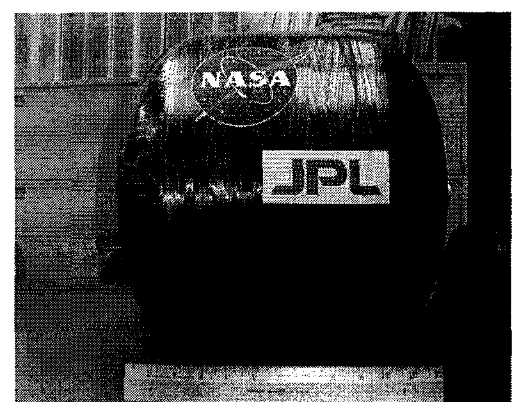
- <u>Mass Reduction</u> Compared to Monolithic Titanium Vessels
  - Two-thirds reduction for high-pressure COPV's
  - Fifty percent reduction for low-pressure COPV's (propellant tanks)
  - 8 kg mass saving for two tanks on MER

- <u>Cost Reduction</u> Compared to Monolithic Titanium Vessels
  - Up to fifty percent reduction for high-pressure COPV's
  - Comparable cost for low-pressure COPV's

- <u>Schedule Reduction</u> Compared to Monolithic Titanium Vessels
  - Up to fifty percent for high-pressure COPV's
  - Up to fifty percent for low-pressure COPV's

Overview
Description of COPV

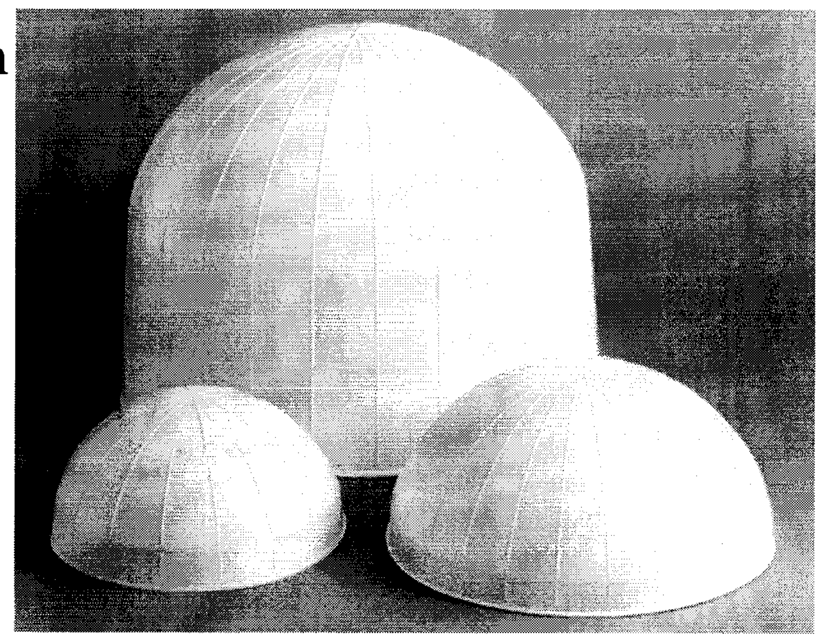
- **Composite Overwrapped Pressure Vessels (COPV) consist of a metallic liner overwrapped with a high-strength fiber/polymeric matrix resin composite**
  - **Non-load-bearing liner provides hermetic seal, stresses are carried by high-strength, low-density composite**
  - **Liner Materials**
    - **Aluminum alloys**
    - **Titanium alloys**
    - Inconel Alloys
    - Stainless Steels
  - **Fiber Materials**
    - **Graphite – 850,000 psi tensile strength**
    - **Polybenzoxazole (PBO) – 800,000 tensile strength**
    - Kevlar
    - Glass
  - **Matrix Resins**
    - **Epoxies**
    - **Isocyanate-base polymers**
    - Polyimides
    - Other polymers



Overview
Description of COPV, continued

- Inside the tank are various types of propellant management devices (PMD)
  - Surface tension and diaphragm are the most common

•Surface Tension:
  - Lightest weight
  - Non-recurring design costs high
  - Not usable in some environments
    - •Aerocapture, landing, missile interception, and other high G loads



•Diaphragm:
  - Lightest weight with positive expulsion (all environments)
  - Never been qualified other than traditional thick Titanium liner

COPV Applications in Aerospace

Status of COPV Technology Within the Aerospace Industry

- **Dedicated safety standard (AIAA S-081) released and adopted by NASA**
- **High-Pressure Applications**
  - **COPV's have totally replaced monolithic titanium vessels for high-pressured aerospace applications**
    - **Pressurant tanks for chemical propulsion systems**
    - **Gas-supply tanks for cold-gas attitude control systems**
    - **Gas-supply tanks for inflation systems, science instruments, etc.**
    - **Xenon propellant tanks for electric propulsion systems**
    - **Tanks for high-pressure liquid reactants e.g., LASERS**
- **Low-Pressure Applications**
  - **Low-pressure propellant tanks are just starting to be flown**
  - **SSTI / Lewis Spacecraft**
  - **CHANDRA**
- **Used in launch vehicles, earth orbiting and planetary spacecraft**

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Near Term Applications of COPVs

Examples

- Mars Recon Orbiter - JPL/Lockheed
  - State-of-the-art 20 mil or greater Titanium liner thickness
- New Millenium ST5 - GSFC
  - Modified Ultralight Aluminum tank liner 10 mil thick
- Airborne Laser - DOD
  - State-of-the-art 30 mil thick stainless steel liner

Buckling of Liners in Composite Overwrapped Pressure Vessels

Description of Problem

- **Liners are above tensile yield at MEOP**
- **Liners are above compression yield at zero pressure**
  - **Composite is elastic and causes liner to yield compressively**
- **Adhesive bond between liner and composite prevents bucking**
- **Lack of bonding or weak adhesion results in buckling**
- **Cyclic buckling causes liner to crack**

Effect of Liner Material

- **Aluminum, titanium and stainless steel liners have buckled**

Effect of Liner Thickness

- **All thicknesses up to practical limits buckle**
  - **0.005 inch, 0.020 inch, 0.030 inch**
- **Making liner thick enough to avoid buckling results in unacceptable mass**
- **Propensity to crack during buckling increases with increasing liner thickness**

Buckling of Liners in Composite Overwrapped Pressure Vessels

Program	Tank Type	Supplier	Tank Size (in)	Liner Mat'l and Min. Thickness (in)	Composite Mat'l	Bondline Adhesive and Thickness (in)	Type of Bondline NDI	Tank Burst Factor	Type of Failure	Failure Detected	Failure Cause
Mars Exploration Rover	Prop	Pressure Technology Division of Carleton	16.2 dia 18.0 length	6061-T62 Aluminum 0.005	PBO / Epoxy	FM-73 0.005	C-scan Ultrasonic (passed)	2.0	Buckled Liner	Visually, during tank assembly after bondline NDI	Yet to be determined
Mars Reconnaissance Orbiter	GHe	PSI	16.7 dia 29.6 length	CP Ti 0.020	Graphite / Epoxy	FM-73 0.005	None	1.5	Liner crack due to buckling	Pressure-cycle test	Unknown
Airborne Laser	Prop	Lincoln Composites	24.0 dia 120.0 length	Annealed Austenitic S.S. 0.030	Graphite / Epoxy	FM-73 0.005	Unknown	2.5	Liner crack due to buckling	Pressure-cycle test	Unknown

Buckling of Liners in Composite Overwrapped Pressure Vessels

- NDI Processes to Detect Buckling
  - All processes require calibration on real tanks with built-in unbonded areas
  - C-Scan Ultrasonic Inspection
    - Coupling is critical
    - Sensitivity needs to be determined
  - Thermal Scans should be assessed
  - Endoscopic Visual Inspection
    - Requires access that will permit all areas of liner to be viewed
    - Not as sensitive as ultrasonic inspection

COPV Supplier Recovery from Buckling Phenomenon

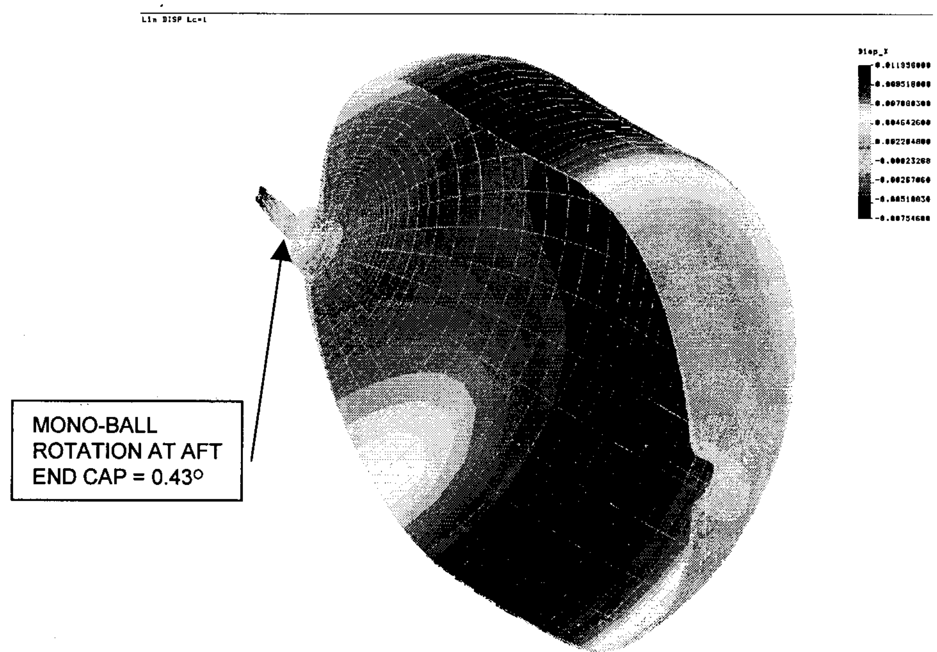
- 5 suppliers
  - Arde, Lincoln Composites, PSI, Carleton, TRW (?)
- Need to re-establish tank integrity
- JPL is qualified to lead a NASA effort to requalify materials/processes/inspection to preclude use of buckled liners in COPV applications
- Preliminary Cost est ~$500k

MER Ultralight COPV History

- Mars Ascent Propulsion System Technology Task
  - 0.005-inch thick aluminum liners, graphite/epoxy and PBO/epoxy
  - Three high-pressure and three low-pressure liner performance demonstration tanks with seamless liners
    - Passed qualification tests
  - Three high-pressure and three low-pressure flight weight prototype development tanks with welded liners
    - Low-pressure tank passed qualification tests
    - One high-pressure tank survived LOx pressure-cycle testing at NASA/MSFC
- Mars Micro Missions Project
  - Started design and qualification of high-pressure pressurant tank, fuel tank and oxidizer tank
    - Propellant tanks were to have internal titanium prop management devices
    - 0.005-inch thick welded aluminum liners, graphite/epoxy (pressurant tank) and PBO/epoxy (Propellant tank) composites
- Mars Exploration Rover Project
  - Designed and fabricated two qualification tanks and one flight tank for hydrazine monopropellant system
    - Internal surface tension titanium PMD's
    - 0.005-inch thick welded aluminum liners, PBO/epoxy composite

Design

- Tank Design completed
  - End Cap re-design completed Oct '01
  - Finite element analysis completed Nov '01
  - Released Source control drawing complete 12 '01
- Stress analysis done (Burst FS 2.0)
  - Peak stress in Titanium aft plug end cap assembly = 34 ksi, MS(yield)=1.8, MS(ULT)=1.6
  - Peak stress in Aluminum Liner is at aft boss radius = 12.6 ksi
  - Peak stress in the aft end cap inertial weld = 3.5 ksi, MS(yield)=2.2, MS(ULT)=2.4
  - Peak combined loads (21.25 G + MEOP) give MS 0.06 (Yield & ult)
- Negligible risk

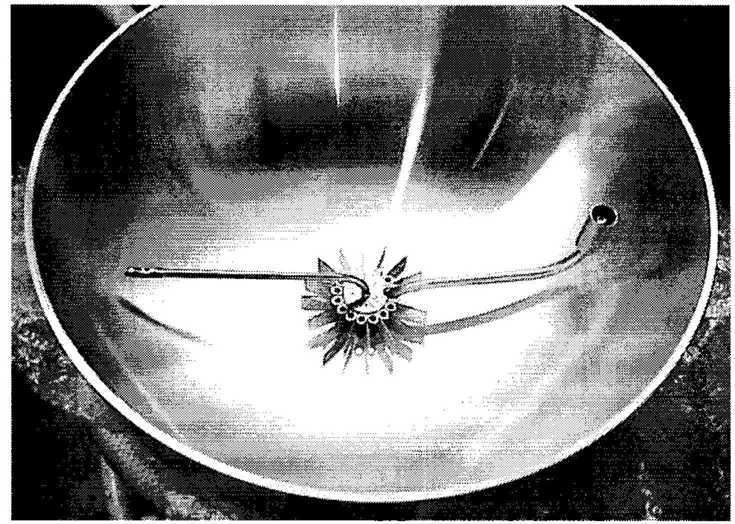


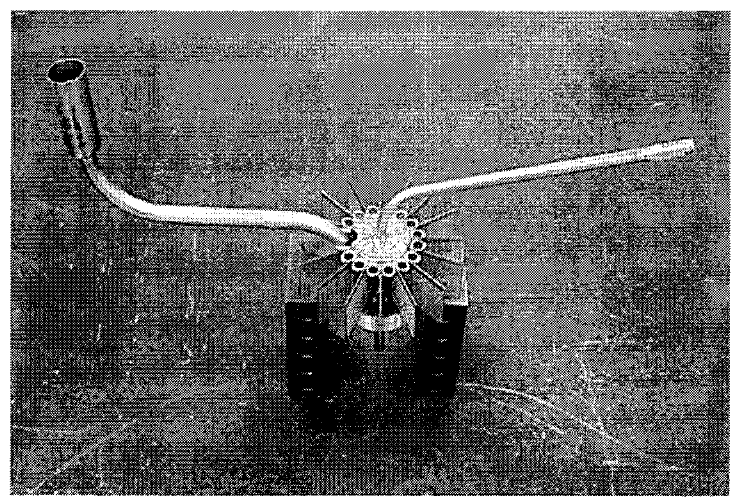
MER Ultralight Tank Fabrication

As machined tank cup shown at right with Propellant Management Device (PMD) in place

Tight tolerance machining to plus/minus 1 mil repeatable demonstrated

Surface Tension PMD design, fab and testing complete



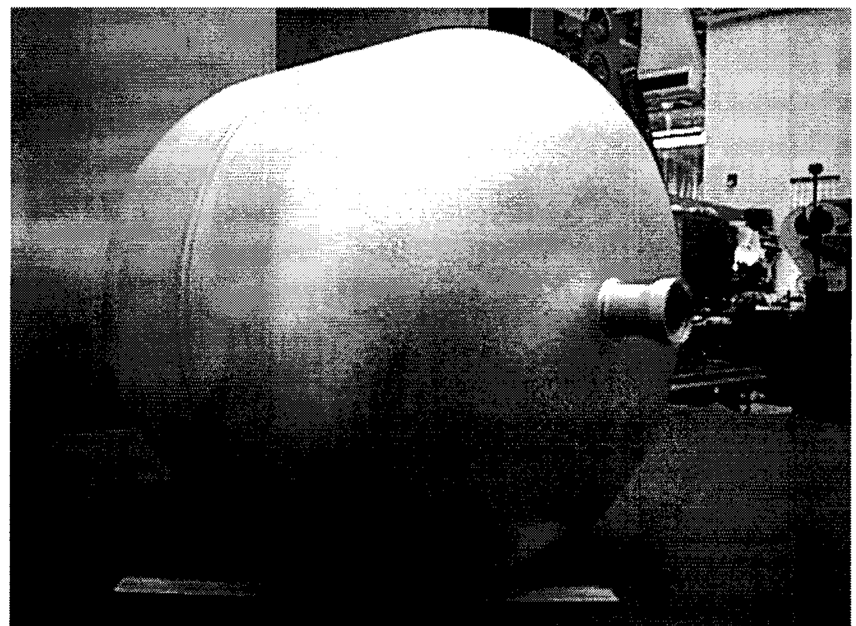


Separate view of PMD

Tank Liner Chemical Milling

- Successfully Chem Milled 6 Mars Micromission liners at 14.6 inch dia. and 8 MER liners at 16.4 inch dia.
  - From .067” to .006” +/- .001” parent metal, weld .030”+/-.001”

- Development weld qual rings successfully chem milled
  - .200” to .020”+/-.001”
  - .067” to .030”+/-.001”
- Negligible risk

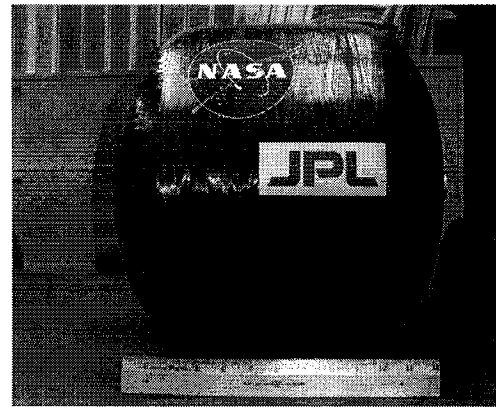


Liner - post chem milling

MER Ultralight Fabrication, continued

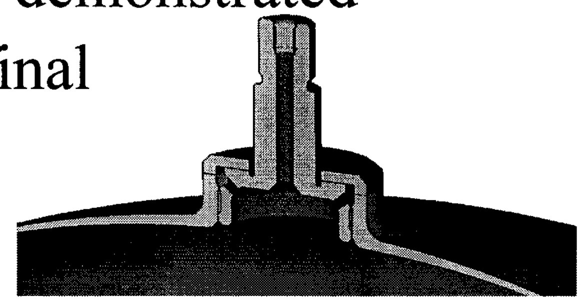
Fiber Overwrapping

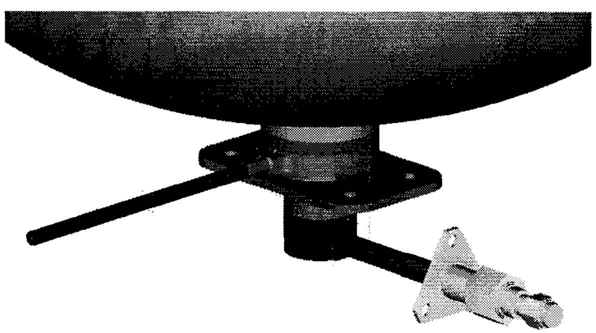
PBO fiber overwrapping repeatably demonstrated

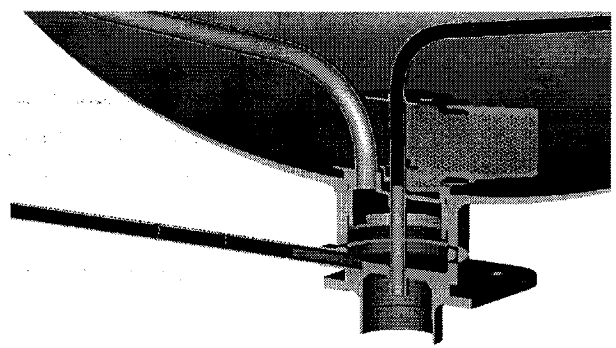


Installing End Caps

- Inertia welding at component level repeatable demonstrated
- EB and TIG welding of sub-assemblies and final assembly are standard processes
- Negligible risk

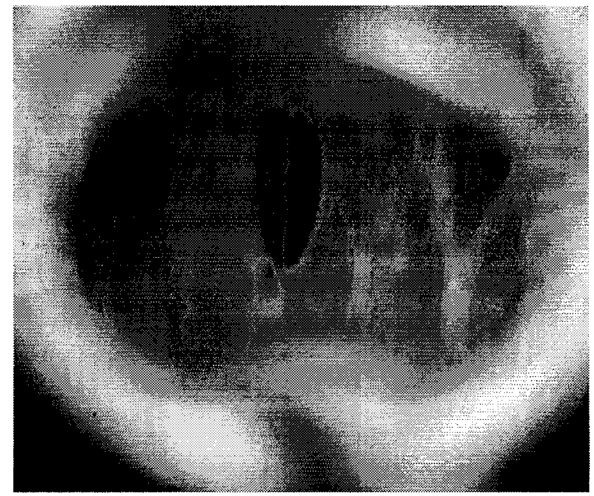






MER Ultralight COPV Residual Issues

- Due to late welding step tank drop outs and one liner buckling problem MER Project Management switched to standard heavy Titanium tank technology in April 2002
- NEEDED: Resolution to buckle phenomenon and a more robust weld process would be economically beneficial to increase tank yield.



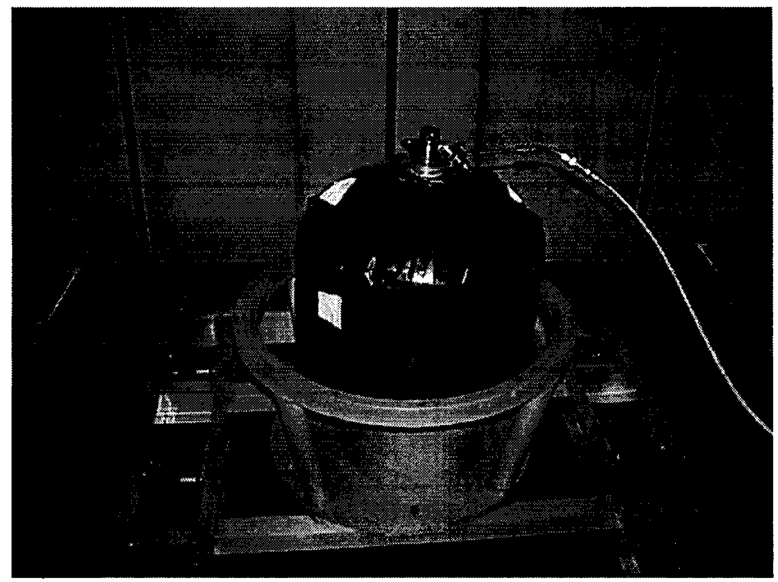
View of liner Buckle about 1 1/2 inch long and 1/2 inch wide

NASA Code S Has Made Significant Investment in Ultralight Tank Technology

Program Sponsor	Dollars Invested, $M	Time Period
Mars Technology	0.7	1998 - 2000
Mars Micromission	0.35	2000
MER Project	2.3	2000 - 2002
Total Code S to date	3.35	1998 - 2000

Relatively Small Cost to Complete Qualification of Ultralights

- MER Project has produced 3 flight "qualifiable" Ultralight tanks - now available
  - Total cost to qualify these tanks is $279K
  - One of these tanks is shown on right with black plastic UV mitigation cover. Pictured is final N2 drying of tank.
  - Final total tank system mass 2.5 kg vs. 5.2 kg for Ti tank (both with service valve)



- MER Project has produced other tanks with weld cracks, one leaker, and one tank with liner buckle
  - Total cost to complete anomaly investigation is $93K
  - To reduce manufacturing fallout, investigate VPPA welding, est cost $350k

Ultralight Tanks - needed now & in the future

- Over 90% of all Team X Propulsion designs assume Ultralight Tanks
- DAWN Discovery Mission will have to drop Ultralights from baseline
- Significant issue in NSI missions e.g. large Xenon tanks
- Commercial benefits

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Ultralight Tank Leak Evaluation

Investigation of Leak in S/N 006 MER Ultralight Tank

Activity	Weeks After Start																	Estimated Cost $
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
Review radiographs of leakage area at Cedtech																		$1,687
Have Cedtech do penetrant inspection of inside surface of weld																		$2,687
Cut leakage area from tank																		$844
Remove composite from liner in leakage area by soaking in NTO																		$5,062
Examine leakage area under high-power optical microscope																		$1,687
Have Cedtech do penetrant inspection of composite side of liner in leakage area																		$1,844
If leak point is located, examine leak point under SEM																		$1,687
If leak point is located, examine leak path metallographically																		$5,062
Prepare Report																		$5,062
Engineering Coordination																		$20,000
Total Cost																		$45,622

Ultralight Tank Buckle Evaluation

Investigation of Buckled Liner in S/N 004 MER Ultralight Tank

Activity	Weeks After Start																	Estimated Cost $
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
Examine original ultrasonic record of bond line inspection																		$1,687
Ship tank to Carleton																		$1,344
Re-inspect bondline in buckled area																		$8,687
Pressure-cycle test tank																		$3,687
Ship tank to PSI																		$500
Cut tank apart and remove PMD																		$844
Cut buckled area from tank																		$844
Open up buckled area for visual inspection of bond line																		$844
Inspect de-bonded surfaces with optical microscope																		$1,687
Prepare Report																		$5,062
Engineering Coordination																		$22,000
Total Cost																		$47,186

Ultralight Tank Flight Qualification

Completion of Qualification of MER Ultralight Tanks

Activity	Location	Cost
Ship Tanks to Carleton	JPL	$3,800
Review records at Carleton	Carelton	$6,470
Proof and Leak Test Tanks	Carleton	$5,940
Pressure-cycle Tests	Carleton	$5,940
Leak Tests	Carleton	$3,470
Ship Tanks to JPL	Carleton	$3,000
Vibration Tests	JPL	$55,470
Ship One Tank to PSI	JPL	$1,340
Bubble Point Test PMD in One Tank	PSI	$4,470
Ship Two Tanks to NTS-LA	PSI / JPL	$1,840
Leak Test Three Tanks	NTS-LA	$9,400
Burst-pressure Test Two Tanks	NTS-LA	$3,940
Ship Two Tanks to JPL	NTS-LA	$1,800
Completion of Qualification Test Procedures	JPL	$15,000
Qualification Test Report/Engineering Oversight	JPL	$157,000
Total Cost		**$278,880**

COPV Summary

- A supplier recovery effort lead by NASA seems to be in order due to liner buckling
  - Preliminary estimate is in range of $500K
- MER Ultralight Tanks were bit by liner buckling late in flight delivery schedule
  - Above effort directly applicable to Ultralights
- Ultralight Aluminum liner COPV is within $375K of being flight qualified; out of $3.35M spent to date -- will In-Space Propulsion fund directly?
  - Dozens of future missions impacted by lack of ultralight